# Rate-adaptive multicast video streaming from teams of micro aerial vehicles

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***Abstract*— Video multicasting from cameras mounted on micro aerial vehicles (MAVs) is desirable for applications such as search and rescue, surveillance and disaster management. Because of the mobility of the video sources and the high data-rate of videos, the transmission rate should be adapted to the task at hand. Rate-adaptive video multicast streaming in 802.11 requires wireless link estimation as well as frequent feedback from multiple receivers. We propose an application layer rate-adaptive video multicast streaming framework using 802.11 ad-hoc network that is applicable when both the sender and the receiver nodes are mobile. The receiver nodes of a multicast group are dynamically elected based on their changing link conditions to gain feedback. An Application Layer Video Multicast Gateway (ALVM-GW) adapts the transmission rate and the video encoding rate based on the received feedback. Emulation results show that the proposed approach has balanced performance in terms of goodput, delay and packet loss.**

## I. INTRODUCTION

Streaming videos from micro aerial vehicles (MAVs) can be used for search and rescue, surveillance, aerial mapping, remote sensing and disaster management [1]–[3]. To offer large-scale situational awareness to multiple users simultaneously, multiple MAVs need to stream videos of different observed areas in a multipoint-to-multipoint fashion to be viewed for example on mobile devices. Viewers shall be able to receive at least an *overview (low definition) video* from all the MAVs. 802.11 is the protocol of choice as it is supported by several MAV platforms [4], is low-cost, widely available, standardized and operates in the licence-free spectrum [5].

Viewers shall be able to select a video from a particular MAV and receive its high quality stream when needed. The selection of a particular video stream by a first responder shall be communicated to the MAV in the range or to the neighboring viewer node to form the video multicast group. Multicasting is an efficient way to transmit identical data to multiple users since it saves network resources compared to unicasting [6], [7]. However, multicast frames in 802.11 are addressed to a group of hosts and are not acknowledged. Since a source has no knowledge of the lost packets or the link condition of the receiver nodes, it cannot retransmit the lost packets or adapt the link transmission rate.

When not all MAVs are in the range of the viewers, videos must be relayed [8], [9] among MAVs or between viewers (Fig. 1). This solution involves multi-hop multicast video streaming, for example using tree driven approaches [10], [11]. These approaches require routing, channel access and high bandwidth when both source and destination points are mobile. Information pertaining to multicast nodes entering and exiting multicast groups needs to be maintained in a decentralized manner to obtain regular transmission feedback from the multicast group members and to regulate the transmission rate based on their link conditions. To deal with the complexity of multi-hop multicast streaming and decentralized group management, we propose an Application Layer Video Multicast Gateway (ALVM-GW) as a central coordination entity.

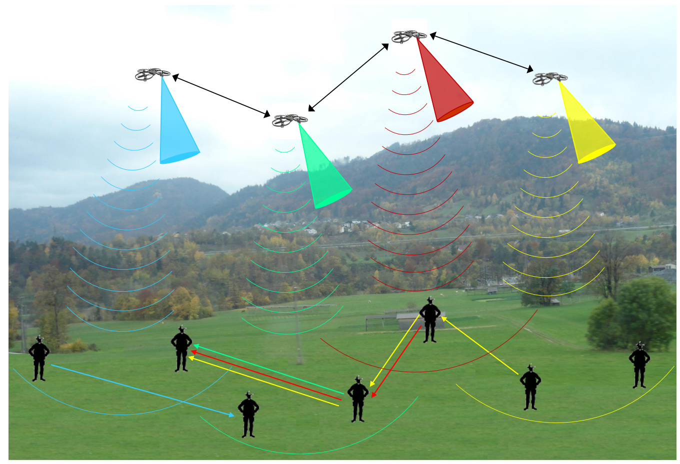

Fig. 1. Multipoint video streaming from a fleet of MAVs to multipoint recipients. MAVs receive video traffic from neighboring MAVs and transmit to recipients in their communication range. Recipient nodes also share received traffic streams among their neighbors.

Existing schemes [12], [13], [14], [15], [16] that address the feedback problem for multicast traffic and adapt the transmission rate require modifications in the medium access control (MAC) layer. The MAC layer of each node joining a multicast group shall be tailored against the requirements of the scheme being used. The node selected amongst the multicast group to provide feedback shall be dynamically elected with changing link conditions due to mobility and shall be made responsive (i.e. be able to provide feedback considering packet reception by all members of the group). Moreover, existing schemes are not designed for highly mobile networks like those formed with MAVs. For this reason, the selection of the node sending the feedback is not dynamic.

In this paper, we address the problem of a two-hop video multicast streaming in mobile wireless ad-hoc networks and we propose a scheme that provides feedback using the application layer, i.e. eliminating the need to alter the MAC layer and making the node providing feedback dynamic

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and responsive. While application layer error correction schemes [16], [17] and application layer multicast tree-driven routing protocols [18], [10], [11] have been already investigated, to the best of our knowledge an application layer multicast approach that regulates the transmission and video encoding rate for highly mobile two-hop network has not been studied yet. The link conditions of the flying MAVs and the mobile recipients change dynamically since the wireless transmission medium intrinsically holds fading and interference characteristics. Thus the rate at which the traffic is being generated and the link transmission rate need to be regulated such that the delay between the receptions of packets is bounded to meet the Quality of Service (QoS) requirements. The rate can only be regulated if feedback for packet reception is provided to the transmitter. We propose to use the application layer to perform these tasks and therefore the proposed solution can be used with any 802.11 supported devices without any modifications to the MAC layer.

The paper is organized as follows. In Section II challenges in multicasting using 802.11 wireless network are highlighted. Section III gives a background on the existing approaches for multicasting and rate adaptation in wireless networks. Section IV gives an overview of the problem being addressed. The proposed rate adaptation scheme for video multicasting in a multipoint-to-point-to-multipoint fashion based on ALVM-GW along with the feedback and rate adaptation process is presented in Section V. The emulation setup and results are presented in Section VI. Section VII concludes the paper.

## II. Multicasting challenges

In addition to limited *transmission range* in wireless networks and network topology changes in mobile networks requiring path discovery and routing [19], [20], challenges with multicasting in 802.11 wireless networks are related to reliability, fairness, performance and delay [12], [17], [21], [22].

The 802.11 protocol multicasts data packets using the broadcast address. A packet with a broadcast/multicast address shall be decoded by all recipients of a multicast group. If all members acknowledge (ACK) the receipt of the packet, the ACK packets will collide and so the source will keep on re-transmitting the same packet for several times. The *reliability* problem stems from the lack of a mechanism that acknowledges reception of multicast packets [23] or retransmissions of lost packets. The challenge is how to make multicasting reliable such that lost packets are retransmitted to the desired recipients.

Since there exists no feedback mechanism in 802.11 multicasting, a source cannot adapt the transmission rate when the receivers link conditions vary. Thus, a receiver node can suffer network congestion due to a bad link condition or it can waste available network resources when it could afford higher bit rates. The objective is to achieve *fairness* through rate adaptation such that the source transmission rate is controlled based on the reception conditions of the members of the multicast group.

The distance, location and reception condition of the wireless members of the multicast group may vary. The reception conditions vary in time and space, and therefore the achievable throughput vary for different members of the multicast group. 802.11 uses the lowest bit rate (1, 2 or 6 Mbps) for multicast traffic. This poses *performance* degradation for the nodes that can afford better bit rates. Ideally, members of the multicast group would receive video data at an individual transmission rate supported by each member, similarly to unicast. However, since this is not possible for multicast traffic, a higher performance can be achieved by transmitting at a rate affordable by all members of the multicast group rather than using the lowest transmission rate as in 802.11 multicasting.

Finally, adhering to strict *delay* bounds between packet transmission and reception, and QoS support for live video multicast [21], [22] streaming is affected by fading, interference, and signal attenuation due to mobility. For example, delays higher than 250 ms are not acceptable for live video streaming [24] but can be experienced when a receiver is three hops away from the source.

## III. Related work

Approaches to gain feedback on packet reception from members of a multicast group over 802.11 wireless access networks can be categorized as: promiscuous reception of unicast transmission, polling schemes and leader-based protocols [17].

In *promiscuous reception*, the source sends data to a member of the multicast group as unicast traffic while other members listen in promiscuous mode [25], [26]. This approach requires every member to be informed of the MAC and IP address of the node receiving the unicast traffic. If the target node leaves the multicast group without informing the source, other members of the group will experience total packet loss.

The *polling scheme* asks every receiver of the multicast group if it has received the packet and otherwise retransmits [14], [15]. Packet ACKs are requested through a control frame called request for ACK (RACK) upon which all members shall respond while the data packet is re-multicast if one of the response is missing. This consumes additional network resources and is inefficient for video multicast streaming.

The *leader-based* approach chooses a member of the multicast group as the leader of the group tasked to send ACKs for the received packets. Negative ACKs (NACKs) can be sent by other members of the group if a packet is not received [13], [12], [27]. The drawback of this scheme is that all members of the multicast group need to handshake with the source to be recognized as the member of the multicast group. The Leader-Based Protocol (LBP) [27] addresses the reliability problem by sending ACKs against the received packets but does not address the other challenges. SNR-based auto rate for multicast (SARM) [13] uses a supplementary link-level signaling to collect signal-to-noise-ratio (SNR) values of the multicast nodes and selects the leader experiencing the worst channel conditions. The rate is adapted based on

TABLE I

SUMMARY OF EXISTING APPROACHES FOR MULTICAST RATE ADAPTATION

| Ref. | Scheme | Needs MAC modification? | Rate adaptation | Evaluation | Multicast groups | Hops | Mobile nodes |
|---|---|---|---|---|---|---|---|
| [14] | Polling based | Yes | User experience in time | Simulation ns-2 | 1 | 1 | 1 |
| [15] | Polling based | Yes | Joint reception correlation | Test bed | 1 | 1 | 1 |
| [13] | Leader based | Yes | Beacon Signal | Simulation ns-2 | 1 | 1 | 3 |
| [12] | Leader based | Yes | Auto rate fallback | Simulation ns-2 | 1 | 1 | 10 |
| Ours | Dynamic leader | No | RTP packet feedback | Emulation | 4 | 2 | 8 |

SNR-PSNR relation such that the peak-signal-to-noise-ratio (PSNR) of the receiver shall be greater than 30 to adapt the PHY rate to 1, 5.5 or 11 Mbps. However, the rate is adapted per beacon signal rather than per multicast data frame. SARM improves QoS and adds reliability but does not address other challenges of performance and fairness. Leader-based Multicast with Auto Rate Fallback protocol (LM-ARF) [12] overcomes the rate adaptation drawback of per beacon signal by using per frame rate adaptation as in 802.11 ARF rate adaptation scheme. The multicast data rate is increased if the AP receives 10 consecutive ACKs from the leader while the data rate is decreased upon 2 consecutive retransmissions. However, a modification in the MAC layer for CTS-to-self frame is required to reserve the channel for multicast traffic. LM-ARF addresses the challenges of reliability through ACKs, performance and fairness through rate adaptation but does not address the challenge of strict delay for video multicasting.

Table I summarizes the schemes described in this section and compares them with our proposed approach.

## IV. Overview of the proposed solution

To reduce the complexity of the multipoint-to-multipoint multicasting we use a *multipoint-to-point-to-multipoint* architecture with a two-hop wireless network topology (Fig. 2). Multiple MAVs unicast video streams to an Application Layer Video Multicast Gateway (ALVM-GW), which (i) transcodes the incoming video streams, (ii) forms multicast groups and (iii) multicasts the videos to the mobile wireless recipients as overview videos. A viewer can then select an overview video to receive its high quality stream.

Let $N$ MAVs stream videos through a shared network channel. Let $C_{R_i}$ be the total network capacity at a given transmission rate $R_i$ where $R_i \in \{6, 9, 12, 18, 24, 36, 48, 54\}$ Mbps for 802.11a. Let $I = \{I_i\}$ and $\mathbb{O} = \{O_i\}$, $i \in \{1, \cdots, N\}$ be the input and output HD video streams at the ALVM-GW, respectively. The transmission rate $R_i$ remains the same for all $O_i$. Let the HD video stream of $O_i$ be encoded at a rate $r_i$.

Let $\mathbb{O}_f = \{O_{f_1}, O_{f_2}, \cdots, O_{f_N}\}$ be the overview video streams and $r_f$ be the fixed encoding rate of $\mathbb{O}_f$ (in our case $r_f = 350$ Kbps). The transmission rate $T_R$ required for multicasting the $N$ video streams is

$$T_R = \sum_{i=1}^{N} r_i + (N \times r_f). \quad (1)$$

The packet loss and video distortion will be minimum if

$$T_R \leq C_{R_i}. \quad (2)$$

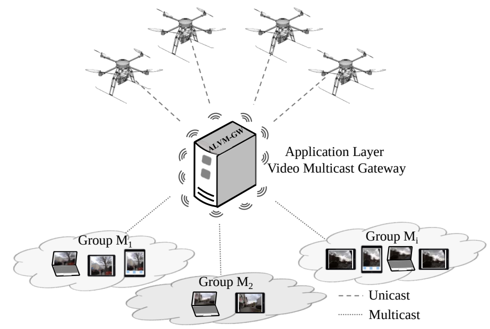


Fig. 2. Multiple MAVs unicast video streams to an ALVM-GW that forms multicast groups and multicasts the videos to the mobile wireless recipients. The ALVM-GW can be a MAV with high processing power, multicasting the incoming video streams from multiple MAVs.

The objective is to regulate all the $r_i$ such that Eq. 2 is satisfied. Once a viewer selects one of the overview videos to receive its high-quality stream, the selection is communicated to the ALVM-GW so that it can create multicast group(s). The encoding rate the ALVM-GW should use to transcode the video stream is the one that allows all viewers of a multicast group to experience seamless and smooth video reception while the receivers are mobile and their reception conditions change frequently.

To solve the problem, we propose an Application Layer Rate Adaptation (ALRA) multicast scheme that selects members of the multicast group based on their signal to interference and noise ratio (SINR) to acknowledge the reception of the packets on behalf of the group. The member with the highest SINR is assigned the role of Primary designated $P$ node. Other members in the SINR hierarchy are assigned roles as Secondary designated $S$ nodes as backup of $P$ node. The feedback received by the ALVM-GW is used for retransmission upon packet loss and for rate adaptation in order to reduce video distortion.

The ALVM-GW performs video transcoding, multicast group management, process feedback and group probing (Fig. 3). Video streams from $N$ MAVs are transcoded to $\mathbb{O}_f$ and $\mathbb{O}$ streams. Multicast groups are formed when members send a join request to the ALVM-GW by selecting a particular video stream to be viewed in high quality. A state table is maintained by the ALVM-GW for the nodes leaving and joining the multicast group. The multicast group management function processes the *join* group, *leave* group and *deregistration* requests. The join request follows the *role assignment* process (Algorithm 1), while the leave request and non response follow the *deregistration* process. The *process feedback* function processes the feedback received from the $P$ and $S$ nodes for rate adaptation. The *probe group*

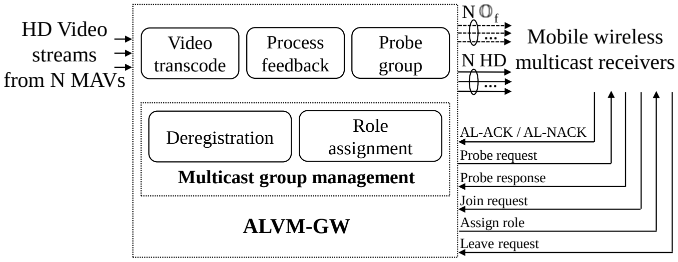


Fig. 3. The application layer video multicast gateway (ALVM-GW) takes in input N high-quality video streams from the MAVs and transcodes them to N low-quality and N high-quality videos. The ALVM-GW manages multiple groups, and adapts transmission and video encoding rates based on the feedback received from the multicast group members.

is a signaling packet sent to the multicast group $M_i$ to get SINR, Node ID and IP information of all the members of the group. Due to mobility and dynamic link conditions of the members of the multicast group, roles are re-evaluated through probing and are re-assigned subsequently.

## V. Application layer rate adaptation

### A. Role assignment and de-registration

The role assignment process defines which members of the multicast group are designated nodes or best effort nodes (Algorithm 1). The video reception of *best effort nodes* is on the best effort basis and these nodes are members of a multicast group that do not provide feedback.

The $P$ node is the one with the strongest link (i.e. the highest SINR) with ALVM-GW. We propose to select less than 50% of the nodes to be the *designated nodes* out of the total number of nodes $n(M_i)$ of the multicast group $M_i$. After the $P$ node, the set of $S$ nodes have the strongest link with ALVM-GW and are assigned IDs representing their hierarchy based on their SINR with the ALVM-GW. The ALVM-GW calculates the SINR $S_V$ of a node $V$ requesting to join a multicast group $M_i$ and assigns the role as designated or best effort member of the group if $S_V > S_T$. $S_T$ is the minimum SINR value required to support minimum rate HD video. The first node that joins the multicast group is assigned the $P$ role if $S_V > S_T$, else the request is denied. A node is assigned the $S$ role if $\frac{1+n(S)}{n(M_i)+1} < 0.5$ (see Table II for notation). A new node joining can change roles between $P$ and $S$ if $S_V > S_P$ or $S_V > S_S$, respectively. Otherwise, it is added as a member to the $M_i$ as best effort $Q$ node.

A *de-registration* process is initiated when a multicast member node requests to leave the multicast group or if there is no response from the node. If the leave request is from a node that is not a designated node, it is removed from the group. However, for de-registration of a designated node the *probe group* function is activated, followed by the *role assignment* process.

### B. Feedback from designated nodes

Feedback from the multicast nodes is required to address the *reliability* challenge. An application layer acknowledgement (AL-ACK) is issued upon packet reception, whereas an

**Algorithm 1:** Role Assignment at ALVM-GW

**Notation**: See Table II.
**Input**: Node $V$ requests for HD video, $S_V$, $S_P$, $S_S$, $n(S)$, $S_T$, $n(M_i)$.
**Output**: Role is assigned to $V$ joining $M_i$.

**if** $S_V > S_T$ **then**
  **if** $n(M_i) > 0$ **then**
    **if** $n(S) > 0$ **then**
      **if** $\frac{1+n(S)}{n(M_i)+1} > 0.5$ **then**
        **if** $S_V > S_P$ **then**
          $M_i \leftarrow V$, $Q = S$, $S \leftarrow P$, $P = V$
        **else if** $S_V > S_S$ **then**
          $M_i \leftarrow V$, $Q = S$, $S \leftarrow V$
        **else**
          $M_i \leftarrow V$
        **end**
      **else if** $S_V > S_S$ **then**
        $M_i \leftarrow V$, $Q = S$, $S \leftarrow V$
      **else**
        $M_i \leftarrow V$
      **end**
    **else if** $\frac{1}{n(M_i)+1} < 0.5$ **then**
      $M_i \leftarrow V$, $S = V$
    **else**
      $M_i \leftarrow V$
    **end**
  **else**
    $M_i \leftarrow V$, $P = V$
  **end**
**else**
  Request is denied
**end**

TABLE II
Notation

| Notation | Description |
|---|---|
| $M_i$ | Multicast groups where $i \in \{1, \cdots, N\}$ |
| $n(M_i)$ | Cardinality of multicast group $M_i$ |
| $V$ | A new mobile receiver node |
| $S_V$ | SINR of $V$ |
| $P$ | Primary designated node |
| $S_P$ | SINR of $P$ |
| $S$ | Set of secondary designated nodes |
| $S_S$ | SINR of $S$ |
| $n(S)$ | Cardinality of the set of $S$ nodes |
| $Q$ | Set of best effort nodes |
| $n(Q)$ | Cardinality of the set of $Q$ nodes |
| $S_T$ | Threshold SINR |

application layer negative acknowledgement (AL-NACK) is issued upon packet loss. While the $P$ node is responsible for sending AL-ACKs to the ALVM-GW (see Fig. 4(a)) upon packet reception, either a $P$ or $S$ node can send a AL-NACK to request retransmission in the case of a packet loss (Fig. 4(b)). Note that the transmission of the AL-NACK involves contention at the MAC layer to gain channel access since it is a data packet from the MAC view-point. However, the ALVM-GW reacts to the first received AL-NACK whereby the pending AL-NACKs are dropped.

The *performance* and *fairness* challenges are addressed through continuous feedback about packet reception and rate adaptation. Since the nodes are mobile, the $P$ node may not

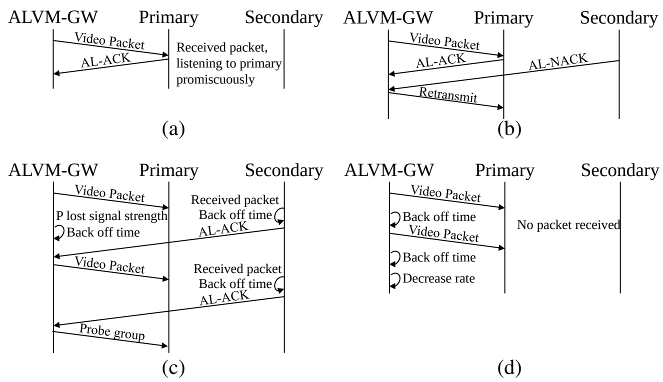


Fig. 4. ALVM-GW video multicasting and reception response from the $P$ and $S$ nodes. (a) $P$ AL-ACKs for the received packets. (b) $S$ generates an AL-NACK for retransmission. (c) ALVM-GW evaluates multicast members link condition and re-assign roles. (d) The ALVM-GW decreases the transmission and video encoding rate upon signal loss.

maintain the strongest link with the ALVM-GW during the whole mission. The $S$ nodes take over in the case the $P$ node fails or loses its signal strength with the ALVM-GW. The $S$ nodes listens to the AL-ACKs sent by the $P$ node in promiscuous mode. If a $S$ node does not hear an AL-ACK from the $P$ node, the highest $S$ node in the hierarchy sends the AL-ACK, and so on. The ALVM-GW retransmits the packet upon AL-NACK or if an AL-ACK is not received and it decreases the video encoding rate. However, before retransmission the ALVM-GW waits for a back off time to get an AL-ACK or AL-NACK from any of the $S$ nodes.

The $S$ node sends an AL-ACK upon packet reception to the ALVM-GW if an AL-ACK or an AL-NACK is not received from the $P$ node. This indicates to the ALVM-GW that the $P$ node no longer maintains the strongest link with the ALVM-GW or is no longer a member of the multicast group. If a feedback is received from the $S$ node while there is no response from the $P$ node, the ALVM-GW sends a *probe group* signal to evaluate the link condition of the members of the multicast group and re-assigns the roles. This scenario is presented in Fig. 4(c).

A loss of feedback indicates either a network congestion problem or that the designated nodes are out of the communication range from the ALVM-GW. The ALVM-GW decreases the transmission rate and the video encoding rate upon signal loss, i.e. when no AL-ACK or AL-NACK is received from any of the $P$ or $S$ nodes, as presented in Fig. 4(d). Nevertheless, a *probe group* signal followed by a *role assignment* process is initiated as soon as the rate is decreased twice consecutively.

### C. Process feedback and rate adaptation

The video encoding and transmission rates are regulated based on the feedback received from the $P$ and $S$ nodes. Inspired by the 802.11 MAC layer rate adaptation schemes, ARF or AARF for 802.11 [28], we propose to adapt the video encoding rate upon two consecutive AL-ACKs or two consecutive AL-NACKs. The encoder is instructed to regulate the video encoding rate for the next Group of Picture (GoP). We increase the video encoding rate for the next GoP upon two consecutive AL-ACKs and lower the rate for the next GoP upon two consecutive AL-NACKs. Because videos are streamed using the Real-time Transport Protocol (RTP), we use RTP Control Protocol (RTCP) signaling to gain feedback about the reception of the RTP packets.

The first AL-ACK or AL-NACK received corresponding to a RTP packet from any $P$ or $S$ nodes is counted. When an AL-NACK is received twice consecutively, the ALVM-GW lowers the video encoding rate by 5%. Therefore the encoding rate is decreased gradually until no feedback about the packet reception is received, i.e. a signal loss. The transmission rate is so decreased upon the signal loss. Similarly, upon two consecutive AL-ACKs the video encoding rate is increased gradually by 5% whereby the transmission rate is increased upon ten consecutive AL-ACKs from the designated nodes.

The transmission rate starts at the lowest rate supported by 802.11a to let the ALVM-GW adjust based on the feedback. Similarly, the video encoding rate is set to 2500 Kbps (encoding rate for 720p HD video), it can increase to 8192 Kbps (the average encoding rate of the input videos) and it can decrease down to $r_{min}$ (an application-dependent parameter, which in our case is set to 350 Kbps).

## VI. Results

### A. Emulation framework

We used the Extendable Mobile Ad-hoc Network Emulator (EMANE) for physical and MAC layers in conjunction with the Common Open Research Emulator (CORE) for the higher layers [29]. EMANE is a framework for modeling mobile network systems in real-time [30], and can be used to emulate the data link and physical layer for mobile and wireless networks. CORE [31] is a real-time network emulator [32]. The Quagga routing suite is configured with CORE for wireless routing OSPF MANET Designated Routing (OSPF-MDR).

Emulated devices represent MAVs that stream their videos to the emulated ALVM-GW. The streaming functionality that includes transcoding of the video sequences is carried out using gstreamer [33]. The downstream video transmissions to the first responders is received as overview videos. Once the first responder selects a particular video for high-quality stream, it joins the multicast group as described in the former sections. The server (ALVM-GW) and client (multicast viewer) applications are implemented in C language. The ALVM-GW acts as a server to multicast multiple video streams encoded at a rate of 350 Kbps for overview videos. The client application receives the video streams and displays them side by side.

Once a video stream for high quality is selected, the request is sent to the ALVM-GW for transmitting the selected video stream. With this, the overview video streams are paused while the window for high quality stream opens up to stream at an allowable video encoding rate. The parameters used for the emulated setup are listed in Table III.

We compare our proposed approach with legacy 802.11a multicast. To simulate dynamically changing wireless link

TABLE III
PARAMETERS USED FOR MULTICAST EMULATION

| Parameters | Values |
|---|---|
| Radio interface | 802.11a |
| Channel frequency | 5 GHz |
| Channel propagation model | Two-Ray |
| Transmission power ($T_x$) | 12 dBm |
| Noise figure | 4 dBm |
| Transmission rate ($R$) | {6, 9, 12, 18, 24, 36, 48, 54} Mbps |
| Maximum transmission unit (MTU) | 1472 Bytes |
| Average input video encoding rate | 8120 Kbps |
| Overview video encoding rate ($r_f$) | 350 Kbps |
| Frame rate | 29.97 fps |
| Area bound | 600 m x 600 m |
| Routing protocol | OSPFv3MDR |
| Emulation time | 600 s |
| No. of runs | 5 |

conditions of the MAVs and multicast members, we use line and random mobility models. With line mobility, MAVs and multicast members move away from the ALVM-GW with a constant speed of 1.33 m/s until they reach a distance of 600 m. With random mobility, MAVs and multicast members move randomly within a given bounded area using a random walk mobility model. Line tests are conducted where the ALVM-GW sends a multicast video stream to the receiver nodes that move away from the source up to a distance of 600 m. A two-ray fading model is used due to the fact that for most wireless propagation cases, two paths (direct path and ground reflected path) exist from transmitter to receiver. We consider $N = 4$ multicast video streams forming multicast groups each having $n(M_i) = 4$ and evaluate the results in terms of goodput, packet loss, delay and video encoding rate.

### B. Discussion

Figure 5(a) presents the goodput at the multicast receiver for the transmission rate of 54 Mbps, 6 Mbps and the rate adaptive scheme. The results are sampled every 3 s with 5 emulation runs. It can be observed that the goodput with the proposed approach increases gradually through rate adaptation as the receiver multicast node moves away from the ALVM-GW until 10 dB SINR and drops with the loss of signal strength.

This behavior is observed since the video is encoded at 2500 Kbps (Fig. 5(b)) at the start and the transmission rate is set to the lowest $R_i$, i.e. 6 Mbps. As the ALVM-GW receives consecutive AL-ACKs the video encoding rate increases and so the goodput also increases. However, since the receiver node is moving away the signal strength decreases, leading to the increased packet loss (Fig. 5(c)). As the ALVM-GW receives AL-NACKs, the video encoding rate is reduced until the receiver node moves out of communication range and the signal is completely lost. The corresponding delays remain under the 250 ms bound (Fig. 5(d)). Although with this scenario the constant bit rate (CBR) traffic with fixed transmission rate at 6 Mbps performs better, if the input HD video stream is encoded at a higher bit rate, e.g. 25 Mbps, higher packet losses will be observed that will prohibit the reception of the video stream. However, with the rate adaptive scheme the video playback remains smooth.

Figure 5(e) - (h) present the goodput, video encoding rate, packet loss and delay, respectively, observed at the primary designated node when four multicast receiver nodes are set static with primary placed at 50 m, secondary at 100 m and two best effort nodes at 200 m. The emulation is run for 600 s to observe the rate adaptation behavior of the proposed approach. As expected, considering the single receiver node results, the video encoding rate is regulated based on the received feedback from the designated nodes. Note that in this scenario $P$ and one $S$ node provide feedback to the ALVM-GW and the rate (transmission and video encoding) is regulated accordingly. This behavior can be observed through the packet loss plot of Fig. 5(g). As the packet loss increases and a feedback is received by the ALVM-GW, the video encoding rate for the next GoP drops and increases with consecutive AL-ACKs. In general, the packet loss for the rate adaptive scheme remains under 10% while for 6 Mbps packet loss peaks beyond 10% are observed. We noticed that the received video gets highly distorted or no playback is seen when the packet loss goes beyond 10% even though the delay for packet reception remains low. Figures 5(i) - (l) show a similar behavior for the best effort nodes. Since the best effort nodes are placed at 200 m, with 54 Mbps as transmission rate the videos are not received at these nodes since they are beyond the communication range.

Figure 5(m) - (p) present the goodput, video encoding rate, packet loss and delay, respectively, for four high-quality video streams with four multicast receivers. The receiver nodes move away from the ALVM-GW using a random walk mobility model. Each receiver selects a different video to be streamed in high quality. Although the results show higher goodput and video encoding rate for 6 Mbps, higher packet loss does not render the playback of the video stream. We observe high goodput for 6 Mbps due to the high encoding-rate. However, since the GoP can be composed over several packets, a low packet loss is acceptable for smooth video reception, otherwise the video is either highly distorted or not received completely. The video reception experience with the proposed rate adaptive scheme remains smooth.

We also conducted emulation for two-hop video streaming. Four MAVs stream videos to the ALVM-GW that in turn stream the videos to the multicast receivers. The MAVs and receiver nodes are mobile using a random walk mobility model while the ALVM-GW remains static. The ALVM-GW adapts the video encoding rate based on the feedback from the designated nodes. Similarly, the MAVs adapt the encoding rate based on the feedback from the ALVM-GW. The two-hop results in terms of goodput, video encoding rate, packet loss and delay are presented in Fig. 5(q) - (t), when four high-quality multicast videos are streamed. The video reception remains smooth as long as the packet loss remains under 20%. The video gets distorted as the packet loss goes beyond 20%. Note that at 6 Mbps and CBR, the two-hop multiple video streams are either not played back or highly distorted.

An example of the received frames with CBR 6 Mbps and rate adaptive scheme for a multistream video multicast

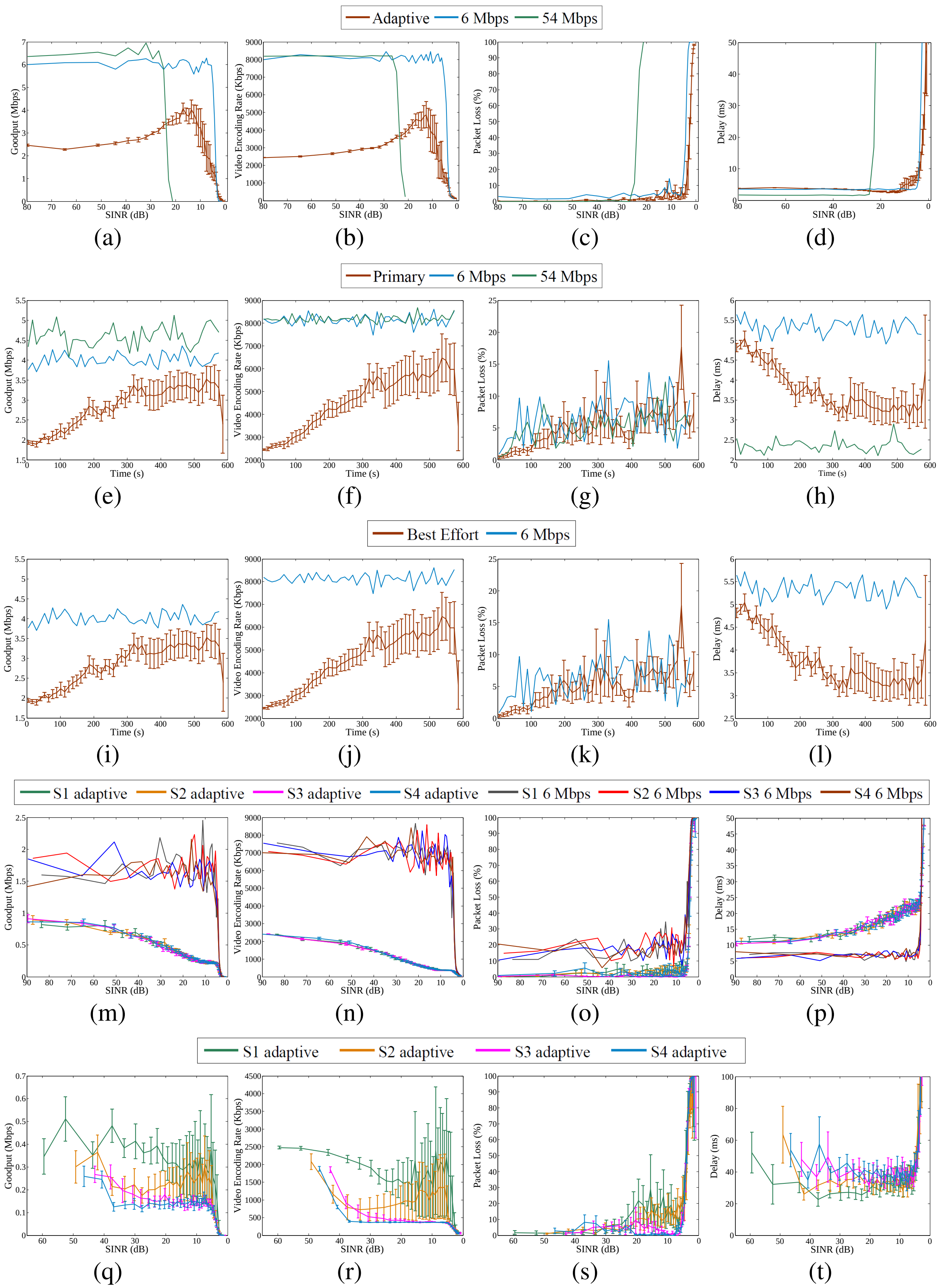


Fig. 5. Goodput, video encoding rate, packet loss and delay for different emulation scenarios. (a) - (d) One video stream multicast to one receiver node when the receiver moves away from the source from 10 m to 600 m. (e) - (h) Measurements at the primary node and (i) - (l) at the best effort node when one video stream is multicast to four receivers. The receiver nodes remain static with primary at 50 m, secondary at 100 m and best effort nodes at 200 m. (m) - (p) Four video streams with four multicast receivers when the receiver nodes move away from the ALVM-GW using random walk mobility. (q) - (t) Two-hop four video stream multicast when the MAVs and the receiver nodes are mobile using random walk while ALVM-GW is static, and in between MAVs and multicast nodes.

Fig. 6. Three sample frames captured at 2 s intervals representing received video quality with CBR 6 Mbps (first row) and rate adaptive scheme (second row) for a multistream video multicast.

is presented in Fig. 6.

## VII. Conclusions

We demonstrated the feasibility of an application layer rate-adaptive multi-video stream multicast that does not require any modification at the MAC layer and is suitable for mobile robotic platforms equipped with cameras. The transmission and the video encoding rates are adapted based on the received feedback from multiple designated nodes. Role switching between multiple receiver nodes (designated nodes) caters for mobility and rate adaptation. The reliability challenge is addressed through retransmission of lost packets while delays under given bounds are met through video encoding-rate adaptation.

Our future work will focus on developing application layer packet-correction codes to reduce the number of retransmissions, enabling higher-quality video stream. Moreover, we will test the performance of the proposed framework using a real testbed.

## Acknowledgments

Raheeb Muzaffar was supported by the EACEA Agency of the European Commission under EMJD ICE FPA n° 2010-0012. A. Cavallaro acknowledges the support of the Artemis JU and the UK Technology Strategy Board (Innovate UK) through the COPCAMS Project, under Grant 332913.

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